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Vision Research 46 (2006) 1946–1958
Vision Research
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Multiple sources of information and time-to-contact judgments ☆

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Received 18 May 2005; received in revised form 1 November 2005

Abstract

Four experiments examined how the visual system deals with multiple information sources for perceiving dynamic events. Two tau-type optical variables, one defined by the expanding object's image and the other defined by the expanding angular extent composed of the line of sight and the object's shadow, were manipulated in time-to-contact judgments. When the information specified by both variables was consistent, little perceptual accuracy was gained by having two information sources. When the two sources conflicted, perceptual accuracy deteriorated in proportion to the degree of conflict. Based on these results, we concluded that the visual system integrates multiple sources of event-specific information, and that a reliable source of information can be the shadows cast by moving objects.

Keywords: Multiple sources of information; Time-to-contact judgments; Cast shadows; Informational conflict; Dynamic events

1. Introduction

Research has identified many sources of information that are potentially available to the visual system to enlighten us about our environment and its layout, e.g., accommodation, convergence, binocular disparity, motion parallax, shadow, perspective, relative size, texture gradients, shading, and many others. Given this list of available information sources, a question arose about how the visual system interacted with the information. Does the visual system rely on a single source or multiple sources of information? Over the years, numerous studies have been conducted to address this question (Bruno & Cutting, 1988; Bülthoff & Mallot, 1988; Cutting, Bruno, Brady, & Moore, 1992; Landy, Maloney, Johnston, & Young, 1995; Massaro & Friedman, 1990, to name a few) and the results generally have provided support for integration of multiple sources. Researchers continue to disagree, however, as to how this integration takes place, and various rules (e.g., averaging, addition, multiplication, weak or strong fusion, etc.) have been proposed (Cutting et al., 1992; Landy et al., 1995; Massaro & Cohen, 1992; Massaro & Friedman, 1990). However, the question remains open.

Not only is the environmental layout specified by various information sources, but so too are events. Consider the case of a projectile approaching an observer (an example of an event involving a moving object). As the projectile approaches the observer, the optical solid angle subtended by its frontal face expands (Fig. 1). The inverse of the relative rate of optical expansion (tau) specifies time-to-contact (TTC) between the approaching object and the observer (Lee, 1976). Numerous studies have been conducted to explore whether this optical quantity is used, not only by humans, but also by a wide variety of animal species to regulate their actions with respect to the surrounding environment (e.g., Bootsma & van Wieringen, 1990; Gray & Regan, 1998; Lee & Reddish, 1981; Savelsbergh, Whiting, & Bootsma, 1991; Schiff & Oldak, 1990). The results of these studies were generally construed to be consistent with what would have been predicted by this optical variable (but see Bootsma, Fayt, Zaal, & Laurent,

☆ We thank Judith Effken for many helpful comments on earlier versions of the manuscript.
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0042-6989/$ - see front matter
doi:10.1016/j.visres.2005.12.011

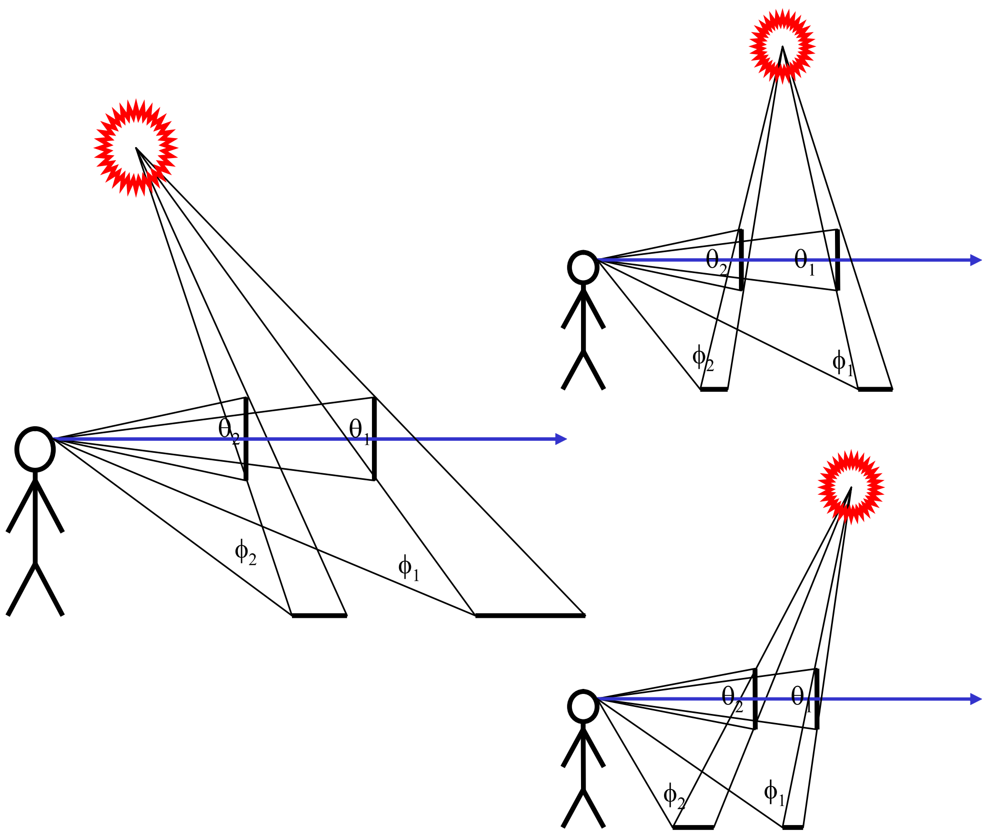

Fig. 1. Geometries of TTC corresponding to an approaching projectile. The visual angle subtended by the frontal face of the object (θ) expands during the approach. The angle defined by the line of sight and a point on the shadow of the object cast on the ground (ϕ) expands concurrently. Hence, two potential sources of information for TTC judgments are available, one defined in terms of θ and the other in terms of ϕ. The former is referred to as tau_{object} and the latter as tau_{shadow}. Note that θ increases (a looming effect) continuously as the object approaches the observer. That is not the case with shadow size, which varies depending on the location of the light source. When the light source is located between the observer and the terminal location of the object (or behind the observer away from the approaching object), the size of the shadow shrinks as the object approaches (left panel). If the light source is located between the starting location and the terminal location of the object, the shadow's size will increase until the object reaches the light source and then shrink as the object passes by (top right panel). If the object is between the light source and the observer, the shadow's size will increase as the object nears the observer (bottom right panel). In brief, there is no consistent pattern in the size of the cast shadow during the approach that can be utilized as TTC information except for tau_{shadow}.

1997; Tresilian, 1997; Wann, 1996, for a continuing debate on issues related to tau).

In the natural environment under normal illumination other information sources may too support judgments of TTC of an approaching object, in particular, the shadow cast by the object onto the surface. Cast shadows have been shown to be an effective source of information for the layout of objects (Braje, Legge, & Kersten, 2000; Kersten, Mamassian, & Knill, 1997; Van de Walle, Rubenstein, & Spelke, 1998; Yonas, Goldsmith, & Hallstrom, 1978; see also Mamassian, Knill, & Kersten, 1998, for a review of perceptual effects of cast shadows; see also articles in the 2004 special issues on *Shadows and Illumination* of *Perception* on various issues involving cast shadows). Moving shadows exerted an even more dramatic effect, inducing vivid impressions of an object moving in depth (Kersten et al., 1997). In addition, moving cast shadows can be utilized as a potential information source for TTC. As depicted in Fig. 1, the inverse of the relative rate of expansion of the visual angle corresponding to the frontal face of the approaching object defines an optical variable tau specifying the object's TTC. The size of the cast shadow is determined largely by the location of the light source, rather than by its distance from the observer, and therefore does not change monotonically as the visual angle subtended by the face of the object (θ) does. This fact rules out change in the size of the cast shadow alone as a source of TTC information. However, the angle defined by the line of sight and a point on the cast shadow (ϕ) expands as the shadow approaches the observer and therefore can be utilized as a potential source of TTC information. In fact, the way this variable is formulated makes it appear very similar to the distance cue, height in the visual field. However, this variable differs from height in the visual field because it is dynamic; that is, the height of the shadow's image in the visual field changes over the course of the approach. This information source is also similar to what

Tresilian (1991) refers to as global tau, but is produced instead by an approaching object, rather than by observer movement.

Hence, just as the perception of spatial layout is facilitated by multiple sources of information; it is conceivable that the same might be true for the perception of events taking place in the environment. If so, event perception researchers must deal with the same unanswered question: How are multiple information sources specifying the same event handled by the visual system? Does one information source dominate, to the exclusion of others; or are multiple sources integrated in some fashion? If integration occurs, how does this transpire? Note that distance cues are assumed to be utilized primarily for the construction of a general purpose three-dimensional internal description of scene. By contrast, optical variables such as tau are assumed to provide control information for the animal's successful encounters with the surrounding surfaces as in interceptive action, locomotion and steering, braking and controlled collision, among others (see Warren, 1998, for a review). These optical variables are therefore highly specialized to supply specific values to the action system to further fine-tune its control parameters with minimal reference to environmental properties. Perhaps redundant information has different implications in this context.

The present study aims to explore these questions. Four experiments were conducted, with TTC as the target event. Computer displays depicted two projectiles approaching the observer along the sagittal plane parallel to the ground plane. The objects floated above the ground during their approaches, thus casting shadows on the ground. TTC was specified in two different ways, first, by the expansion of the visual angle subtended by the approaching object ($\text{tau}_{\text{object}}$) and second, by the expansion of the angle defined by the line of sight and the cast shadow ($\text{tau}_{\text{shadow}}$) (Fig. 1).

Since Lee's (1976) classic study, TTC and its specification through the optical variable tau have been investigated extensively and a number of optical variables with similar informational content have been identified. A taxonomy proposed by Tresilian (1991) has become a convenient tool to classify various tau-type optical variables. Of the three distinct types identified, two are defined in terms of a local perturbation in optical flow, in particular, the expansion of the visual angle subtended by an approaching object, and is referred to as *local tau*. The third results from the global transformation arising from observer translation, in particular, the expansion of the angular extent defined by motion vector and a surface patch, and is referred to as *global tau*. All three types of tau have been extensively investigated, and substantial evidence has been collected demonstrating human observers' sensitivity to these optical variables (see Kaiser & Hecht, 1995; Kaiser & Mowafy, 1993, for the efficacy of global tau in tasks referred to as time-to-passage (TTP) judgments; see also Kerzel, Hecht, and Kim, 1999).

The optical pattern corresponding to $\text{tau}_{\text{shadow}}$, as depicted in Fig. 1, differs from those identified in Tresilian's (1991) taxonomy. Not only is it produced by an approaching object, but also the resultant perturbation in cast shadows is largely local, confined, as it is, to a local region of the flow field. Thus, the conditions eliciting $\text{tau}_{\text{shadow}}$ are similar to local tau, according to Tresilian's classification. On the other hand, because $\text{tau}_{\text{shadow}}$ is defined by angular expansion corresponding to the line of sight and cast shadow on the ground, its optics are more comparable to those of global tau. In short, $\text{tau}_{\text{shadow}}$ shares some similarities with the three types of optical tau identified by Tresilian (1991) but also has its own unique characteristics.[1]

Because $\text{tau}_{\text{object}}$ and $\text{tau}_{\text{shadow}}$ are both potentially available when a projectile approaching an observer casts its shadow on the ground, this scenario can be used to explore how the visual system responds to multiple information sources for dynamic events.

In the real world, few ground surfaces are without texture. But more importantly, as an object moves against the backdrop of a textured surface, its approach velocity can be specified by the rate at which edges or discontinuities of the texture elements are swept by the moving object. This information (i.e., edge rate) is also available by shadows as they move over surface texture elements. Evidence exists that human observers are sensitive to edge rate information (Andersen, Cisneros, Atchley, & Saidpour, 1999; Flach, Warren, Garness, Kelly, & Stanard, 1997; Larish & Flach, 1990). In conjunction with the evidence that human observers base their TTC judgments on the ratio of perceived distance to velocity (Cavallo & Laurent, 1988; McLeod & Ross, 1983; Smeets & Brenner, 1995), edge rate can be used as a potential information source for the computation of this ratio, thereby, providing additional information for TTC. In the light of this, we also controlled ground texture in the experiments.

The projectiles were depicted as cubical objects that appeared with or without a textured ground surface, depending on the condition. Because the edges of the projectiles were all parallel in depth, they provided a strong linear perspective (as defined by the presence of converging lines in the projection) in the display—even in the absence of ground texture. The presence of linear perspective is particularly important in the present study. If human observers are indeed sensitive to $\text{tau}_{\text{shadow}}$, then the visual system must be able to register accurately the vertical visual angle subtended by the line of sight to the horizon and the shadow. How might the visual system extract this angle? The line of sight to the horizon always coincides with eye level (see Sedgwick, 1983, for further discussion). But even without a visible horizon, there is ample evidence in the literature on visually perceived eye level that human observers utilize pictorial cues such as pitched surface and lines

[1] It should be noted that the optical pattern engendering $\text{tau}_{\text{shadow}}$ differs from those patterns induced by non-spherical objects, in particular, oval objects, that Gray and Regan (2000) and Scott, Li, and Davids (1996) employed to investigate TTC judgments. Although these patterns are notable for being non-symmetrical, unlike most of the patterns employed in TTC studies, they still remain as local perturbations.

(e.g., Matin & Fox, 1989; Matin & Li, 1994) or linear perspective cues (Post, Welch, & Clark, 2000) or even optical flow (Wu, He, & Ooi, 2005) to perceive eye level. Hence, veridical depiction of linear perspective, in conjunction with the radial flow pattern engendered by the projectiles and their moving shadows, ensures that this optical quantity is available to the visual system.

Experiment 1 examined the effect of redundant information on TTC judgments. Performance in the $\text{tau}_{\text{object}}$ alone condition was contrasted with performance in the combined conditions of two taus with the additional control of edge rate through background texture. Experiment 2 examined the utility of $\text{tau}_{\text{shadow}}$ in the judgments of TTC. The objects floated high above the ground, thereby excluding $\text{tau}_{\text{object}}$ from the field of view. Experiments 3 and 4 examined the issue of information integration by rendering shadows at non-veridical locations, thus creating conflict between the information provided by $\text{tau}_{\text{object}}$ and $\text{tau}_{\text{shadow}}$.

Other studies have addressed the same issue, namely, the effect of multiple information sources on TTC judgments (Gray & Regan, 1998; Heuer, 1993; Laurent, Montagne, & Durey, 1996; Rushton & Wann, 1999). But the informational multiplicity in these studies was generated using a combination of a binocular source (specifically, binocular disparity) and optical looming (i.e., $\text{tau}_{\text{object}}$). The present study differs from these because of its unique focus on the utility of $\text{tau}_{\text{shadow}}$ and the resultant multiplicity of event-specific information in conjunction with $\text{tau}_{\text{object}}$. As a way of addressing the issue of multiple information sources, we employed the relative TTP judgment paradigm. Although this paradigm has its limitations (see Tresilian, 1995, for further discussion), we felt that a relative judgment task would be preferable to an absolute judgment task, which tends to produce large systematic and variable errors (see also Bootsma & Craig, 2002; Kaiser & Mowafy, 1993; Kerzel et al., 1999, for examples of studies employing a similar methodology for related reasons). Two projectiles approached the observer. When the TTP value for the projectile with the shorter TTP (i.e., the one set to reach the observer's frontal plane earlier) reached 2 s, the display terminated. At that time, participants chose the projectile that they felt would have reached them first had the projectiles continued on their current path.

2. Experiment 1: Redundant information

2.1. Method

2.1.1. Participants

Fourteen undergraduates at the University of Connecticut participated in the experiment in partial fulfillment of a course requirement. All subjects had normal or corrected-to-normal vision.

2.1.2. Apparatus

Displays were generated in real time on a Silicon Graphics Indigo[2] Maximum Impact R10000 and presented on a 21-in. (53.3 cm) screen drawn at a 60 Hz refresh rate. The display had a pixel resolution of 1280 horizontal (H) × 1024 vertical (V) pixels and subtended 42 deg (H) × 32 deg (V), and was viewed from a projectively correct distance of 50 cm in a dimly lit room. Although their eye and head movements were not restricted, they were encouraged to keep their gaze at mid-screen.

2.1.3. Stimuli

Displays were simulations of two projectiles approaching the observer along the sagittal plane parallel to the ground plane (Fig. 2). Each object was depicted as a hexahedron (i.e., a polyhedron of six faces), but the resulting hexahedrons were different sizes. The larger object was 1.8 m (Width) × 1.6 m (Height) × 1.5 m (Depth) and the smaller object was 0.6 m (W) × 1.0 m (H) × 2.8 m (D).

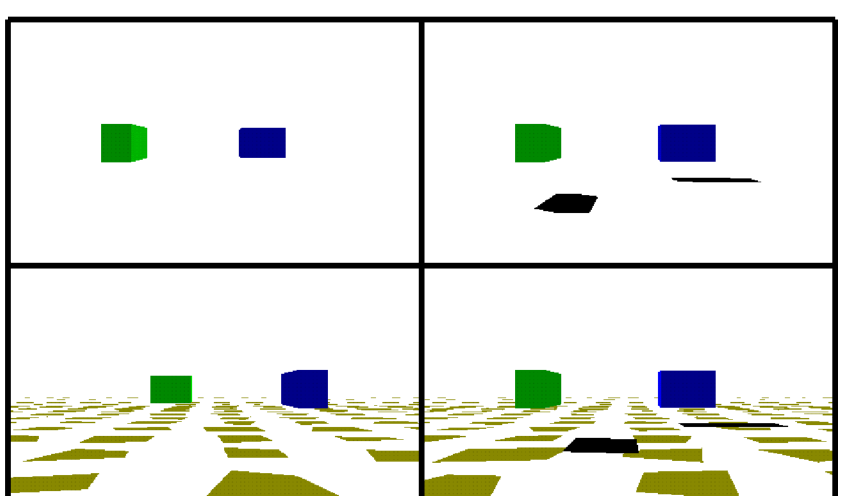

Fig. 2. Displays used in Experiment 1—displays without ground texture (top) or with ground texture (bottom); displays without cast shadows (left) or with cast shadows (right). Two different-sized projectiles approached the observer along the sagittal plane parallel to the ground plane.

The center of the frontal surface of each object remained at eye level during the approach, but was displaced 2 m laterally from the saggital plane corresponding to the center of the screen. An observer's eye height was assumed to be 1.6 m, which corresponded to the center of the vertical dimension of the screen.

The simulated ground plane in the texture condition was 60 m wide and 80 m deep. This rectangular region was further partitioned into 500 cells, 25 partitions horizontally and 20 partitions along its depth. An irregularly shaped polygon, for which the extent of each side was randomly determined, was placed in each cell.

In the shadow condition, a hard shadow (see Braje et al., 2000, for the distinction between hard and soft shadows) of each object was cast on the ground surface (right panel of Fig. 2). The shadows were drawn as perspective images from a local light source (see Blinn, 1988/1996, for details). We manipulated the shadows to start at different locations across trials, by randomly varying the location of the light source according to the following ranges of values: −40 to 40 m along the horizontal dimension; 25–75 m along the vertical axis above the ground; and 10–60 m along the depth axis. These ranges were chosen to keep the shadows within the display area throughout each trial. Because both objects and shadows were moving, the hard shadows were easily recognized as shadows of the corresponding objects. The colors of the left object, right object, and ground texture elements were green, blue, and yellow, respectively, but because of shading due to lighting, their shades changed accordingly.

2.1.4. Design

Six variables were controlled in the experiment. Objects' approach velocities (m/s) varied among the pairs of (6.1, 9.1), (15.2, 12.2), (9.1, 15.2), and (12.2, 6.1), with the first value corresponding to the left object and the second to the right object. The leading object's TTP was fixed at 4 s, whereas the trailing object's TTP varied among 4.125, 4.25, 4.5, and 5.0 s. The pair of values for approach velocity and TTP determined the starting location of each object. Both objects disappeared after the first 2 s. Hence, in the ground texture condition, the ground plane remained even after the objects disappeared. The ground textures were either absent or present, as were shadows of the objects. As noted above, the two objects used in the display were different in size. Last, either the right or left object could arrive at the frontal plane first. Despite the counter-balancing of the leading and trailing objects in terms of left and right, the displays engendered were not the same because, for the approach velocity pair chosen in each condition, the first value was used for the left object and the second value for the right object. In other words, the same velocity was used for one object regardless of whether it was leading or trailing.

These manipulations yielded a 4 (Velocity) × 4 (TTP Difference) × 2 (Shadow: Presence vs. Absence) × 2 (Object Size) × 2 (Lead Object: Left vs. Right) × 2 (Ground Texture: Presence vs. Absence) design for a total of 256 completely randomized trials. All variables were controlled within-subjects.

2.1.5. Procedure

Trials were initiated when the participant pressed the space bar to trigger the display. Participants were told to watch the display until it terminated then indicate, by pressing a key on the keyboard, which object would arrive at their frontal plane first. The entire experiment, including debriefing, took about 30 min.

The experiment was preceded by a practice session of eight trials in which two pairs of approach velocities [(9.1, 15.2), (12.2, 6.1)] were crossed with two object sizes and two lead object conditions. Shadow and texture were included in the practice trials with the TTP difference fixed at 750 ms. Feedback was provided during the practice session, but was not given during the experiment.

2.2. Results and discussion

Mean percentage of correct responses is presented as a function of TTP differences between the two approaching objects for the four approach velocity pairs in Fig. 3. Overall, participants were quite reliable in judging the TTP of approaching objects. Performance at four (125, 250, 500, and 1000 ms) TTP difference conditions was 56%, 62%, 74%, and 86% correct, respectively. Even the 125 ms TTP difference condition with the smallest TTP difference was discriminated above chance, $t(13) = 3.81$, $p = .002$.

The effects of lead object and object size were negligible, $t(13) = 1.17$, $p = .26$ and $t(13) = 1.45$, $p = .17$, respectively. For further analyses, responses were collapsed over these two factors and entered into a repeated measures analysis of variance (ANOVA) with approach velocity, shadow, texture, and TTP difference as variables. The ANOVA revealed main effects of TTP difference, $F(3,39) = 104.75$, $p < .0001$, $\eta_p^2 = .89$; approach velocity, $F(3,39) = 8.43$, $p < .001$, $\eta_p^2 = .39$; and a significant Velocity × TTP difference interaction, $F(9,117) = 2.47$, $p = .013$,

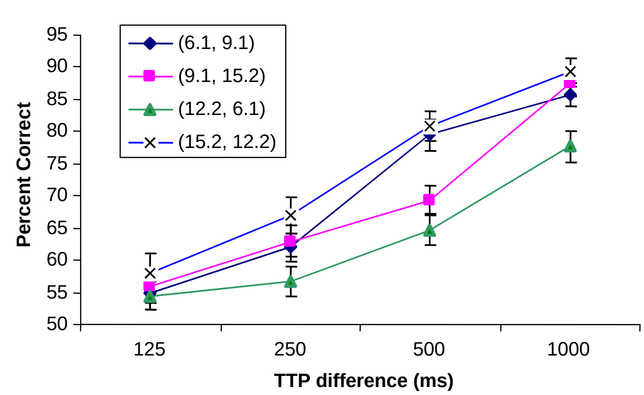

Fig. 3. Mean percentage of correct responses (with standard error bars) as a function of TTP difference (ms) between two approaching objects for four approach velocity pairs in Experiment 1.

$\eta_p^2 = .16$ (Fig. 3). However, the effects of shadow and texture were not significant (both Fs < 1); although their interaction reached a marginal level of significance, $F(1, 13) = 4.58$, $p = .052$, $\eta_p^2 = .26$.

With respect to the main effect of TTP difference, performance improved with an increase in TTP difference. In fact, performance of the participants in this study was comparable to performances reported in similar TTP studies (Bootsma & Craig, 2002; Kaiser & Mowafy, 1993; Kerzel et al., 1999). Note that the values of TTP difference employed in the present study were 125, 250, 500, and 1000 ms, whereas those in the comparable TTP studies were 250, 500, 750, and 1000 ms.

The main effect of approach velocity is consistent with a similar effect observed in other TTC or TTP studies. Kerzel et al. (1999) noted that their participants appeared to rely on optical image velocity rather than global tau in judging TTP (see also Kim, Effken, & Carello, 1998, for a similar finding; see also Andersen et al., 1999, for the effect of velocity on tau-dot, the time derivative of tau). Because approach velocity interacted significantly with TTP difference, to further explore the effect of approach velocity, a simple effects analysis was performed. The effect of approach velocity was significant at 250, 500, and 1000 ms [$F(3, 39) = 3.12$, $p = .037$; $F(3, 39) = 14.88$, $p < .0001$; $F(3, 39) = 4.75$, $p = .006$, respectively]. Most notable was the performance in the 500 ms TTP difference condition (Fig. 2). With velocity differences of (6.1, 9.1) and (15.2, 12.2), accurate performance was 79% and 81%, respectively; whereas with velocity differences of (9.1, 15.2) and (12.2, 6.1), accurate performance was 69% and 65%, respectively. Note that, in the former pairs, the velocity difference between two objects was 3 m/s, whereas in the latter pairs it was 6.1 m/s. When the difference in approach velocities was large, participants appeared to be more susceptible to choosing an object with a faster approach velocity at the point of display termination despite the longer TTP specified by tau.

Of particular significance to the present study were the non-significant effects of shadow and ground texture. Participants were equally accurate with or without a cast shadow and with or without ground texture.

In summary, the results of Experiment 1 suggest that the effect of redundant information on the perception of a dynamic event is minimal. Performance was as accurate when $\text{tau}_{\text{object}}$ was the only source of information as when $\text{tau}_{\text{shadow}}$, texture, or both were added. At a minimum, three different interpretations can be offered to account for these results. One interpretation suggests that the visual system may have tuned into the most salient feature of the visual input, namely, the looming pattern and the associated optical variable, $\text{tau}_{\text{object}}$, and simply ignored other redundant sources of information. This possibility is further reinforced by the recent finding by Franconeri and Simons (2003) who report that the stimuli that signal behaviorally urgent events such as looming and translating objects capture attention even in the absence of any explicit goals. It is also consistent with neurophysiological evidence for neurons that respond to optical patterns involving looming (Field & Wann, 2005; Rind & Simmons, 1999; Sun & Frost, 1998; Wang & Frost, 1992).

Alternatively, the results may reflect the possibility that the informational content conveyed by the two types of tau is the same. In other words, both $\text{tau}_{\text{object}}$ and $\text{tau}_{\text{shadow}}$ provide absolute metric information, namely, the TTC between an approaching object and the observer. This interpretation can be contrasted with that pertaining to the perception of spatial layout through various distance cues. Distance cues convey different messages. Some specify the ordinal arrangement of the surrounding surfaces; others specify metric properties. Moreover, the range within which each cue is effective differs (Cutting & Vishton, 1995). Thus, these cues, when conjoined, facilitate the perception of the surrounding environment. Unlike distance cues, tau (the optical information specifying TTC) provides an absolute metric and therefore the effect of conjoining similarly structured optical variables such as texture or shadow may be minimal.

It is also possible that the results may have simply reflected the fact that the visual system is not sensitive to the optical perturbation corresponding to $\text{tau}_{\text{shadow}}$ and therefore could have not utilized it at all in this task. The ubiquity with which human observers encounter the situation depicted in the present study argues against such an interpretation. It is even more unlikely, in light of the finding by Kersten et al. (1997) that cast shadows facilitated the perception of spatial layout. Still, this possibility demands immediate attention before further pursuing the topic of the present study, that is, the effect of redundant information on the perception of dynamic events. Experiment 2 explored this issue, that is, whether the visual system is sensitive to the optical pattern corresponding to $\text{tau}_{\text{shadow}}$ and utilizes it for the judgments of TTP.

3. Experiment 2: Moving shadows as an information source for TTP

In the natural environment, it is not unusual to experience a situation where the object and its expansion pattern are occluded from view (e.g., when the roof of a car occludes an airplane flying overhead and the only source of information about the approaching airplane is its shadow projection). The displays employed in Experiment 2 depicted such a situation. Specifically, the two objects depicted initiated their flight paths high above the ground; only their cast shadows were shown in the display. Unlike the expansion of the optical angle subtended by the approaching object, the size of the cast shadow does not change monotonically over the course of the approach (as shown in Fig. 1), but is largely determined by the location of the light source. Yet, the angular extent defining $\text{tau}_{\text{shadow}}$ expands during the approach. To assess the efficacy of $\text{tau}_{\text{shadow}}$ more accurately, the displays we used incorporated these effects. In particular, we varied the heights of the two objects by placing the objects sometimes at different locations and sometimes at the same location. As in Experiment 1, we varied the light source and two different object sizes, all of which induced variations in the resulting shadow images.

3.1. Method

3.1.1. Participants

Thirteen undergraduates at the University of Connecticut participated in the experiment in partial fulfillment of a course requirement. All subjects had normal or corrected-to-normal vision.

3.1.2. Stimuli

The same apparatus, viewing geometry, and graphic simulations used in Experiment 1 were used in Experiment 2 except for the heights of the two objects, which varied between 8 and 12 m above the ground. Under this arrangement, the objects were visible during the first few frames of each display then disappeared, as if occluded by the top of the monitor, leaving only their shadows visible on the ground (Fig. 4).

3.1.3. Design

As in Experiment 1, six variables were controlled in the experiment. Of these six, four variables (approach velocity, ground texture, leading object, and object size) were identical to those used in Experiment 1. Unlike Experiment 1, only two TTP difference values, 500 and 1000 ms, were used. The heights of the two objects (in meters) varied among the pairs (10, 10), (12, 8), and (8, 12), with the first value corresponding to the left object and the second to the right object.

The preceding manipulation yielded a 4 (Velocity) × 2 (TTP Difference) × 3 (Objects' Heights) × 2 (Object Size) × 2 (Lead Object: Left vs. Right) × 2 (Ground Texture: Presence vs. Absence) design for a total of 192 completely randomized trials. All variables were controlled within-subjects.

3.1.4. Procedure

The same eight-trial practice session used in Experiment 1 was used in Experiment 2. Because different displays were employed in Experiment 2, participants were specifically instructed about the circumstances of the simulations prior to the main experiment. Participants were told to think of the monitor as analogous to the windshield of a car. As two objects (for example, planes) fly from a point somewhere in front of the observer over the car, the objects will be occluded by the roof of the car but their shadows will remain visible on the ground. Participants were asked to judge, when the display stops, which object, left or right, would pass them first. As in Experiment 1, feedback was provided during the practice session, but was not given during the experiment.

3.2. Results and discussion

As in Experiment 1, responses were collapsed over factors of lead object and object size and converted to percent correct. The result was then entered into a repeated measures ANOVA with TTP difference, velocity, object height, and texture as variables. The ANOVA revealed main effects of TTP difference, $F(1,12) = 147.61$, $p < .0001$,

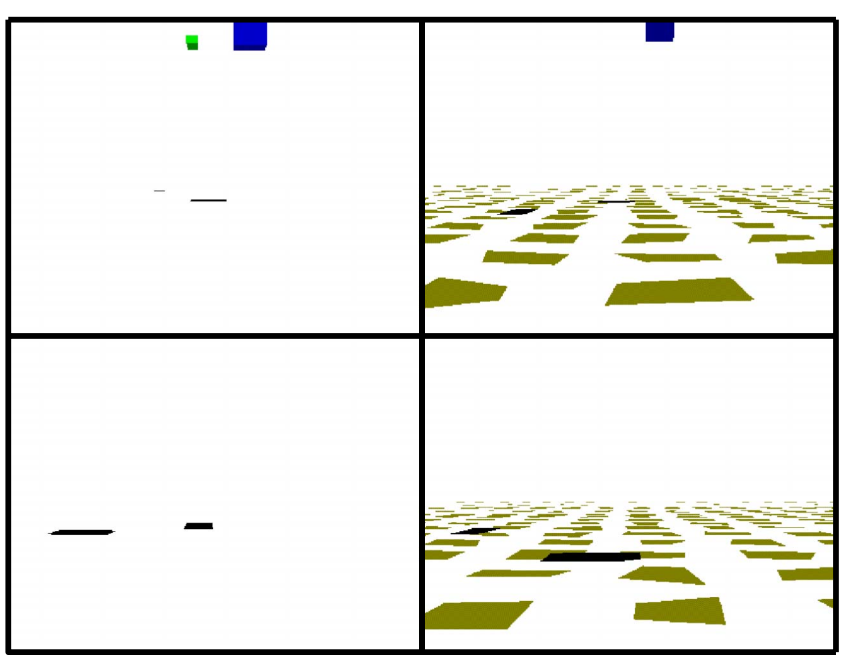

Fig. 4. Displays used in Experiment 2—at the onset of the display (top) or at the end of the display (bottom); displays without texture (left) or with texture (right).

$\eta_p^2 = .93$ (top panel of Fig. 5), and velocity, $F(3,36) = 16.71$, $p < .0001$, $\eta_p^2 = .58$, replicating the results of Experiment 1. The ANOVA also revealed a main effect of texture, $F(1,12) = 9.92$, $p = .008$, $\eta_p^2 = .45$. Performance degraded with ground texture (76% in the texture condition but 79% in the no texture condition) (bottom panel of Fig. 5). The ANOVA also revealed two significant interactions, one between approach velocity and height, $F(6,72) = 9.97$, $p < .0001$, $\eta_p^2 = .46$, and a three-way interaction involving approach velocity, height, and TTP difference, $F(6,72) = 4.29$, $p = .001$, $\eta_p^2 = .26$.

The results largely replicated those of Experiment 1. Performance in the two TTP difference conditions was 71% (500 ms) and 84% (1000 ms) accurate, respectively, comparable to the 74% and 85% accuracies observed in the same conditions in Experiment 1.[2] It appears that participants in this experiment were capable of exploiting the moving shadow of an approaching object, in particular, the optical pattern engendering tau_{shadow}, in judging TTP of the approaching object. The effect of texture supports this conclusion. As noted above, the shape and size of cast shadow did not change monotonically over the course of the approach, let alone expand in the same way that the visual angle corresponding to the frontal face of the inducing object did (see Fig. 1 for illustrations). Hence, shadow alone could not have engendered any local tau-type optical pattern that may have provided TTC information. This leaves two possibilities: Perhaps the visual system utilized the distance to velocity ratio to compute TTC values. If so, ground texture in which edge rate becomes more salient should have facilitated performance. On the contrary, texture was not only not beneficial, but actually impaired performance. Thus, the results can be construed as evidence that the visual system is not only sensitive to the optical pattern corresponding to tau_{shadow} but also utilizes it to the judgments of TTC.

Although the effect of velocity is largely the same as that reported in Experiment 1, it carries different implications in Experiment 2. Because the primary optical variable manipulated in Experiment 1 was tau_{object}, the variation in approach velocity induced a change in the rate of expansion of the visual angle corresponding to the frontal face of the object. In Experiment 2, changes in velocity induced corresponding changes in the rate of expansion of the angular extent composed of the line of sight and cast shadow. The implication of this effect manifested in two different optical patterns is difficult to explain and is left for clarification to future research.

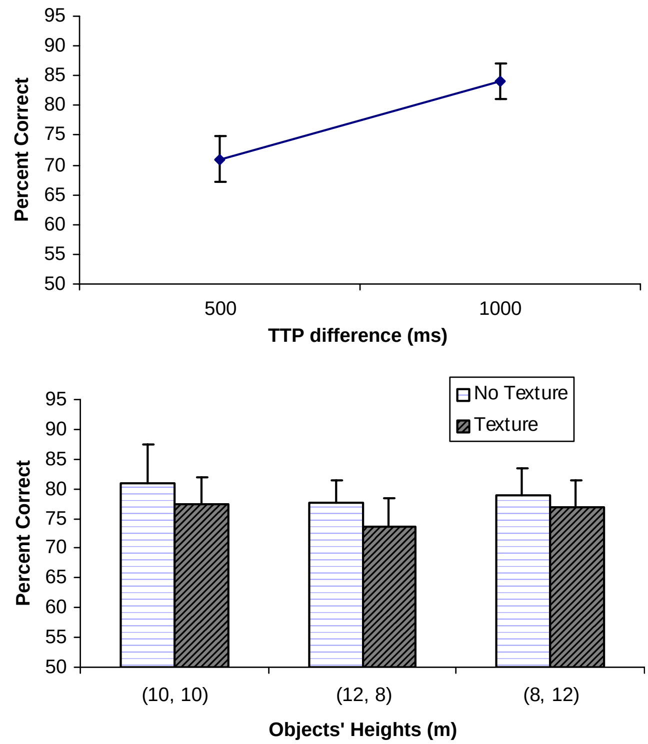

Fig. 5. Mean percentage of correct responses as a function of TTP difference between two approaching objects (ms) (top panel) and as a function of the heights of two objects for two texture conditions (bottom panel) in Experiment 2. Error bars represent 95% confidence intervals.

In summary, tau_{shadow} appears to be an effective source of information for TTC judgments. The finding leaves two possibilities that could account for the results of Experiment 1, the dominance of tau_{object} over other redundant sources of information or the same informational content of each information source with minimal cumulative effect. Experiments 3 and 4 assessed the two remaining alternatives, this time utilizing the conventional technique in cue integration, namely, informational conflict.

4. Experiment 3: Informational conflict

Cast shadows were rendered surreptitiously at non-veridical locations in order to induce informational conflict. This manipulation was motivated by Kersten et al.'s (1997) study demonstrating the susceptibility of the visual system to illusory motion from shadows. Specifically, the leading (or shorter TTC) object's shadow was pushed backward or the trailing (or longer TTC) object's shadow was pulled forward from their veridical locations. Thus, the TTC value specified by tau_{object} was placed in direct conflict with the TTC value specified by tau_{shadow}. If the looming pattern is a natural attention-capturing stimulus, thereby

[2] Note that tau_{shadow} is defined with respect to the line of sight. In the experiments reported here, no specific efforts were made to control participants' gaze except for asking them to fixate their gaze on the middle of the screen throughout each trial. As noted earlier, research on visually perceived eye level provides strong evidence that eye level can be perceived accurately if a linear perspective cue is available. However, we were concerned that some measure of gaze control might be needed to ensure that the performance we observed was indeed based on the observers' sensitivity to tau_{shadow}. Hence, we conducted a control experiment that largely replicated Experiment 2, but employed a fixation point and a head and chin rest. The performance of five participants, all drawn from the Leicester University community, replicated the performance of participants in Experiment 2. In particular, accuracy in the two TTP difference conditions was 68% and 85%, respectively, which is comparable to the performance observed in Experiment 2 for the same conditions.

suppressing other redundant information sources, the effect of this manipulation would be minimal. In other words, if $\text{tau}_{\text{object}}$ is the dominant source of information for TTC judgments, the conflicting information conveyed by $\text{tau}_{\text{shadow}}$ would exert negligible influence on the perceptual outcome. If, however, event-specific sources of information are integrated, performance should deteriorate when these sources are put in conflict. That is, the perceptual outcome would be a compromise between the values specified by $\text{tau}_{\text{object}}$ and $\text{tau}_{\text{shadow}}$.

4.1. Method

4.1.1. Participants

Seventeen undergraduates at the University of Connecticut participated in the experiment in partial fulfillment of a course requirement. All subjects had normal or corrected-to-normal vision.

4.1.2. Stimuli

The same apparatus, viewing geometry, and graphic simulations used in Experiment 1 were used in Experiment 3, except for the non-veridical shadow conditions wherein each object's shadow was cast at non-veridical locations.

4.1.3. Design

As in the previous experiments, six variables were manipulated. Five variables were identical to those used in Experiment 2: approach velocity, ground texture, leading object, object size, and two pairs of TTP differences, 500 and 1000 ms. Shadows were either placed at their veridical locations (the veridical shadow condition) or at the non-veridical locations (the non-veridical shadow conditions). For the non-veridical shadows, either the leading object's shadow was pushed backward by 500 ms or the trailing object's shadow was pulled forward by 500 ms. This yielded a 4 (Velocity) × 2 (TTP Difference) × 3 (Shadow: 1 Veridical and 2 Non-veridical) × 2 (Object Size) × 2 (Lead Object: Left vs. Right) × 2 (Ground Texture: Presence vs. Absence) design for a total of 192 completely randomized trials. All variables were controlled within-subjects.

4.1.4. Procedure

The same procedure used in Experiment 1 was used in Experiment 3.

4.2. Results and discussion

As in the previous experiments, responses were collapsed over factors of lead object and object size and converted to percent correct. The results were then entered into a repeated measures ANOVA with velocity, TTP difference, shadow, and texture as variables. The ANOVA revealed main effects of TTP difference, $F(1,16) = 102.16$, $p < .0001$, $\eta_p^2 = .87$, and velocity, $F(3,48) = 7.41$, $p < .001$, $\eta_p^2 = .32$, replicating the same effects found in Experiment 1.

The ANOVA also revealed a main effect of texture, $F(1,16) = 6.24$, $p = .024$, $\eta_p^2 = .28$. Recall that the effect of texture was non-significant in Experiment 1 but significant in Experiment 2. In fact, the latter effect was even construed as supporting evidence for human observers' sensitivity to the optical pattern corresponding to $\text{tau}_{\text{shadow}}$. The response pattern revealed here, however, was exactly opposite to that observed in Experiment 2. Perception improved in the presence of ground texture (76% accuracy), but degraded in its absence (73% accuracy). Perhaps, the perceptual system was seeking additional information sources, in this case, ground texture, as a way to enhance perceptual quality, which was somewhat compromised due to informational conflict—thus, the improved perceptual outcome in the presence of the ground texture. At this juncture, however, further comments will be reserved until more data become available in Experiment 4.

More importantly, the ANOVA demonstrated a main effect of shadow, $F(2,32) = 9.86$, $p < .001$, $\eta_p^2 = .38$. A Tukey post hoc test confirmed that performance in the veridical shadow condition differed from performance in the non-veridical shadow conditions at the 0.01 level. Performance degraded with non-veridical shadows with degradation proceeding irrespective of the direction in which the non-veridical shadows moved as well as the amount of TTC separation (Fig. 6).

Note that the informational content conveyed by $\text{tau}_{\text{shadow}}$ was compromised, whereas that conveyed by $\text{tau}_{\text{object}}$ was intact. Degraded perceptual outcome in correspondence with the amount of informational conflict, therefore, is an unequivocal demonstration that the visual system integrates various sources of event-specific information. In addition, the results are further evidence that the visual system is sensitive to the optical pattern corresponding to $\text{tau}_{\text{shadow}}$, reinforcing the finding from Experiment 2.

Of interest in interpreting the current results are the contrasting performance patterns reported in studies by Heuer (1993) and by Rushton and Wann (1999). As noted earlier,

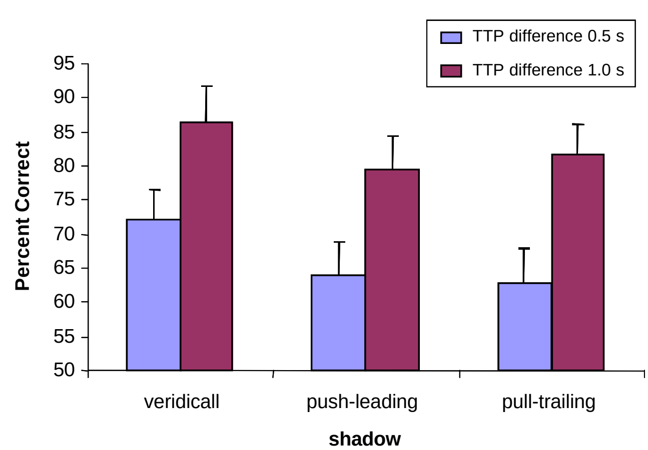

Fig. 6. Mean percentage correct as a function of shadow for two TTP difference values in Experiment 3. Error bars represent 95% confidence intervals.

these studies examined the effect of two information sources, one binocular (target vergence in the Heuer study and binocular disparity in the Rushton and Wann study) and the other monocular (tau_{object}) on TTC judgments. Of particular relevance to the present issue are the results observed under the cue conflict conditions. Heuer reported a pattern similar to that observed in our experiments; that is, performance compromised TTC estimates. Also consistent with the present results was Heuer's finding that the effect of each information source on TTC estimation differed, with tau_{object} exerting more influence than target vergence. Rushton and Wann (1999), on the other hand, observed little degradation in their participants' judgments, with only small TTC errors. They construed this result as a biased response to the more immediate cue (i.e., the cue specifying the shortest TTC). Specifically, they argued that the visual system switches the weighting assigned to each source, ultimately selecting the cue that is seen as most "informative" for the particular task. They reported that this was true both under cue conflict (Experiment 1) and cue loss (Experiment 2). The authors offer little justification for their claim, however, and their claim is not consistent with the present finding. Recall that the manipulation adopted for these experiments was done surreptitiously; that is, despite the fact that the two information sources were put into conflict, our participants were not aware that that was the case. In other words, unless the visual system is endowed with a priori knowledge of which information source is more informative it is not clear how it selects the more veridical source. Instead, the fact that performance degraded in accordance with the amount of informational conflict suggests that the visual system integrates both sources of TTC information, regardless of their relative usefulness.

To gain further insight into this issue, however, we conducted Experiment 4 with a special focus on the extent to which perceptual outcome degrades in proportion to the degree of informational conflict. We expect to gain further insights into not only the way in which the visual system resolves informational conflict, but also the manner in which it integrates various sources of information.

5. Experiment 4: Degree of informational conflict

In Experiment 4, we specifically manipulated the degree of non-veridicality of cast shadows in order to explore the extent to which conflicting information sources influence the perceptual system. To be specific, the amount of conflict was manipulated directly by controlling the differences between the values specified by tau_{object} and those specified by tau_{shadow}.

5.1. Method

5.1.1. Participants

Twelve undergraduates at the University of Connecticut participated in the experiment in partial fulfillment of a course requirement. All participants had normal or corrected-to-normal vision.

5.1.2. Stimuli

The same apparatus, viewing geometry, and graphic simulations used in Experiment 3 were used in this experiment.

5.1.3. Design

The same six variables employed in Experiment 3 were used in this experiment except for the shadow manipulation. All shadows in Experiment 4 were rendered at non-veridical locations by pushing the leading object's shadow backward and pulling the trailing object's shadow forward simultaneously. The push and pull were on the orders of 125, 250, and 500 ms. When combined, the amounts of non-veridicality were 250, 500, and 1000 ms, respectively. The degree of non-veridicality was confined within this range of values to minimize the artificiality of non-veridical shadows. When the degree of each shadow's non-veridicality exceeded 500 ms, the shadow appeared unnatural.

Whether defined in terms of tau_{object} or in terms of tau_{shadow}, each TTC value chosen determined the difference in arrival times between two objects. Thus, the information conflict engendered by this manipulation can be quantified as follows: For the 500 ms TTP difference condition (specified by tau_{object}), the corresponding values specified by tau_{shadow} were 250, 0, and -500 ms, respectively. For the 1000 ms condition, on the other hand, the values were 750, 500, and 0 ms, respectively. To better illustrate the derivation of these values, consider the 1000 ms TTP difference/500 ms shadow condition. Suppose that object A is the leading object, set to arrive earlier than object B by 1000 ms. At the beginning of the trial, TTP for object A (i.e., the value specified by $tau_{objectA}$) would be set to 4 s whereas that for object B (i.e., the value specified by $tau_{objectB}$) would be 5 s, respectively, thus constituting the 1000 ms TTP difference condition. On the other hand, the value specified by $tau_{shadowA}$ ($tau_{objectA}$ + 0.25 s) would be 4.25 s whereas that specified by $tau_{shadowB}$ ($tau_{objectB} - 0.25$ s) would be 4.75 s, thus constituting the 500 ms shadow condition. If the visual system relies on tau_{object} to judge TTC of approaching objects, A would be perceived to arrive earlier than B by 1000 ms. If, however, the visual system relies on tau_{shadow}, the arrival time difference would be only 500 ms (i.e., 4.75–4.25 s), a discrepancy of 500 ms. Note that the negative value of tau_{shadow} in the 500 ms TTP difference/1000 ms shadow condition indicates that the information specified by both optical variables is qualitatively different; that is, each optical variable predicts that a different object will arrive first.

5.1.4. Procedure

The same procedure used in the previous experiment was used in Experiment 4.

5.2. Results and discussion

Responses were collapsed over factors of lead object and object size and converted to percent correct. The result was then entered into a repeated measures ANOVA with velocity, TTP difference, shadow, and texture as variables. The ANOVA showed main effects of velocity, $F(3,33) = 6.30$, $p = .002$, $\eta_p^2 = .36$, and TTP difference, $F(1,11) = 81.14$, $p < .0001$, $\eta_p^2 = .88$, replicating the effects found in the previous experiments. The ANOVA also revealed a main effect of shadow, $F(2,11) = 11.12$, $p < .001$, $\eta_p^2 = .50$. Also significant were the Shadow × TTP Difference, $F(2,22) = 6.42$, $p = .006$, $\eta_p^2 = .37$, and Velocity × Texture × TTP Difference, $F(3,33) = 2.97$, $p = .046$, $\eta_p^2 = .21$, interactions. Unlike Experiment 3, however, the effect of texture was not significant, $F < 1$.

Performance degraded in accordance with the degree of non-veridicality of shadow (Fig. 7). Tukey post hoc tests showed that performance in the 1000 ms shadow condition was different from performance in the 250 and 500 ms shadow conditions at the 0.05 level. These differences were further qualified by the Shadow × TTP Difference interaction. Particularly poor performance in the 500 ms TTP difference/1000 ms shadow condition appears to be the source of this interaction. In fact, performance in this condition did not even rise above chance level, $t(11) < 1$, ns. Note that this is the condition in which the degree of informational conflict was at its maximum. But more important, under this condition, the informational contents conveyed by the two optical variables were qualitatively different, each optical variable predicting that a different object would arrive first. In all other conditions, informational conflict was largely quantitative, that is, TTP differences specified by $\text{tau}_{\text{object}}$ differed from those specified by $\text{tau}_{\text{shadow}}$. In fact, it is noteworthy that, despite the fact that both variables conveyed essentially the same information, the perceptual outcome was influenced by the degree of informational conflict. To better assess the degree to which performance was affected by the degree of conflict, pairwise comparison using the Tukey HSD test was performed. The results of this test confirmed that performance in the 500 ms TTP difference/1000 ms shadow condition differed from performance in the other five conditions at the 0.05 level. Also significantly different were performance in the 500 ms TTP difference/250 ms shadow condition and that in all three conditions of shadow in the 1000 ms TTP difference condition. Finally, performance in the 500 ms TTP difference/500 ms shadow condition differed from performance in both the 1000 ms TTP difference/250 ms shadow and the 1000 ms TTP difference/500 ms shadow conditions, as did performance in the 1000 ms TTP difference/1000 ms shadow condition with respect to the latter two conditions. In brief, the two conditions with minimal information conflict (i.e., the 1000 ms TTP difference/250 ms shadow and the 1000 ms TTP difference/500 ms shadow conditions) elicited the best performance. Conditions with the same degree of informational conflict (i.e., the 1000 ms TTP difference/1000 ms shadow and the 500 ms TTP difference/500 ms shadow conditions) elicited a similar level of performance. Hence, degradation in perceptual accuracy was in proportion to the degree of informational conflict. The only exception was the 500 ms TTP difference/250 ms shadow condition, in which performance degraded further than the 1000 ms TTP difference/1000 ms shadow condition, the condition with a lesser amount of conflict. However, this performance did not differ from performance in the 500 ms TTP difference/500 ms shadow condition, a condition with the same amount of information conflict with the 1000 ms TTP difference/1000 ms shadow condition. In short, performance degraded proportionate to the degree of conflict until the annihilation of the effectiveness of the sources of information with qualitatively distinct informational content.

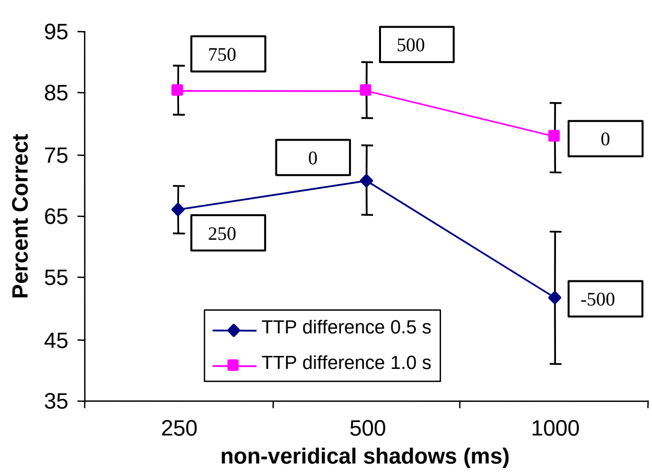

Fig. 7. Mean percentage correct as a function of the degree of non-veridicality of shadow (ms) for two TTP difference values in Experiment 4. The numbers on the graphs depict the degree of informational conflict between two optical variables determined by the differences between TTP values specified by $\text{tau}_{\text{object}}$ and TTP values specified by $\text{tau}_{\text{shadow}}$. Error bars represent 95% confidence intervals.

Also notable was the non-significant main effect of texture. Recall that its effect in the previous three experiments was inconsistent. In particular, the presence of ground texture was negligible in Experiment 1, detrimental in Experiment 2, and beneficial in Experiment 3. Because Experiment 4 is an extension of Experiment 3, it may be more relevant to discuss the role of texture in the context of just these two experiments. With respect to the main effect of texture found in Experiment 3 we suggested that the perceptual system might search for additional information sources when perceptual quality is compromised by the presence of informational conflict and additional information sources might resolve the ambiguity. One major difference between Experiments 3 and 4 is the fact that informational conflict occurred in two thirds of the trials in Experiment 3, whereas all trials employed in Experiment 4 contained informational conflict, but in varying amounts. Perhaps the benefits of incorporating additional information sources are negligible when the primary sources of information are in full conflict. With respect to the three-way interaction involving velocity, texture and TTC, its cause is unclear and we leave this effect for future consideration.

In summary, the results of Experiment 4 further strengthen the observation made in Experiment 3. The visual system integrates various sources of information but it does so in what appears to be an additive manner, as demonstrated by degraded perceptual accuracy in proportion to the degree of informational conflict. Performance deteriorated with an increase in informational conflict between two optical variables, tau_{object} and tau_{shadow}.

6. General discussion

The present experiments explored the issue of multiple information sources for the perception of a dynamic event. With TTC as the target event, two optical variables, referred to as tau_{object} and tau_{shadow}, respectively, both engendered by the same approaching object and thus concurrently available in optical flow, were pitted against each other. The results were straightforward. When conjoined, their cumulative effect was negligible on the perceived quality of the event (Experiment 1). When in conflict, however, perceptual accuracy deteriorated in proportion to the degree of conflict (Experiments 3 and 4).

Based on these results, we conclude that the visual system integrates multiple sources of event-specific information. Moreover, unlike distance cues, for which the integration rules are currently under debate, integration of event-specific information appears to proceed in a linear additive fashion. This conclusion, however, should be evaluated with some caution because the cumulative effect was observed only when redundant information sources were in conflict (cf. Heuer, 1993). When the sources were all veridical, as in Experiment 1, their combined effect was negligible. This may have resulted from the fact that the event-specific information examined here is largely absolute and metric in nature, thereby exerting little to no effect on perception when conjoined, but degrading perception when in conflict.

This conclusion contrasts with Rushton and Wann's (1999) contention that the visual system switches the weighting of each source in favor of the more immediate cue on TTC judgments. Perhaps, as Rushton and Wann suggest, the visual system may be more sensitive to binocular information for small objects and more sensitive to optical looming for large objects (see also Gray & Regan, 1998, for a similar observation). This may be why, given the task of catching a small virtual tennis ball, their participants switched cues that specified the shortest TTC from trial to trial. This still begs the question, however, as to why the visual system selects one cue over the other solely based on its immediacy, especially for TTC judgments. Clearly, more data are needed to evaluate these contrasting findings.

The present results were also consistent with Kersten et al.'s (1997) finding that cast shadows can be a reliable source of information for spatial layout. In the present study, however, cast shadows were utilized as an effective source of information for the perception of a dynamic event (Experiment 2).

Many issues still remain. Of these, one issue demands careful consideration. As Mamassian et al. (1998) point out, linking shadows to the objects that cast them is not a trivial problem, especially in static scenes. In dynamic scenes, however, its complexity diminishes substantially because of the correlated motion between an object and its shadow. But the task confronted by the visual system in the present study goes beyond the task of linking two image patches. First, the visual system has to register two optical variables manifested in optical flow as two different patterns, one (tau_{object}) as a local perturbation and the other (tau_{shadow}) less explicitly as a quantity based on the perceived angular extent defined by the line of sight and a point on the shadow. Moreover, this task has to be carried out against a backdrop of myriads of other events taking place concurrently. Note that, just as the target event may consist of multiple perturbations, so do other events. Hence, the perturbations present in the flow field would be multiples of the number of events with which the visual system is confronted. Yet, the visual system not only perceives an event reliably but it does so while differentiating the event from the rest of the other events whose patterns are contained concurrently in the surrounding energy media.

Perceiving an event reliably in a natural environment is by no means a simple task. How might the visual system accomplish this feat in daily encounters with surrounding surfaces on a regular basis? Pursuing this issue further, however, is beyond the scope of the present study and therefore is left for future research. We hope, nonetheless, that findings from this study will motivate future research along these lines.

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